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Single Shot Multispectral Multidimensional Computational Imaging Using Quasi-Random Lenses

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Abstract: Quasi-random lenses (QRLs) were fabricated using electron beam lithography and conventional lens grinding to map every object point to a unique random intensity distribution. Multidimensional and multispectral computational imaging has been demonstrated using the QRLs.

1. Introduction

Coded aperture imaging technologies have revolutionized the field of imaging in the recent years [1]. In coded apertures, chaotic coded apertures along with computational reconstruction methods have been found to possess interesting imaging capabilities to distinguish depth and wavelength simultaneously even with a monochrome sensor [2, 3]. In many cases, the chaotic coded apertures were implemented using spatial light modulators (SLMs) which are expensive, have low light throughput due to polarization sensitivity and low resolutions. Alternative approaches are needed for improving the performances of chaotic coded aperture imaging methods. Recently, a quasi-random pinhole array was manufactured and implemented for 4D imaging of static objects [4] as well as recording fast-transient events [5]. Even though the performances of the quasi-random pinhole array were satisfactory, the photon budget requirement was significantly higher resulting in a low signal to noise ratio for imaging of astronomical objects and biological samples. In a recent study, we designed a binary polarization independent quasi-random lens (QRL) using the Gerchberg-Saxton algorithm, fabricated it using electron beam lithography and implemented it for single shot white light 3D imaging [6]. The fabricated diffractive element exhibited a high light throughput. In this study, we demonstrate high efficiency 4D imaging in 3D space and spectrum using a similar QRL. An alternative approach was attempted by grinding refractive lenses and slide glasses with sandpaper of different grit sizes. The experimental results with diffractive QRL and semi-synthetic 4D imaging results using scattering lenses manufactured using lens grinding are presented.

2. Methods and experiments

The optical configuration of the imaging system is shown in Fig. 1(a). The light from an object is modulated by a QRL and recorded by a monochrome sensor (Thorlabs, DCU223M, 1024 pixels × 768 pixels, pixel size = 4.65 μm). The optical microscope image of the central part of the QRL fabricated using electron beam lithography (RAITH-150-TWO) is shown in Fig. 1(b). The QRL-sensor distance was 10 cm and the point spread functions (PSFs) were recorded for 10 cm and 9 cm object-QRL distances using a 100 μm pinhole for red (λ = 617 nm, $\Delta\lambda$ = 18 nm) and green (λ = 530 nm, $\Delta\lambda$ = 33 nm) wavelengths respectively as shown in Figs. 1(c) and 1(d) respectively. Two objects NBS (10 lp/mm) and USAF (Group 2, Element 2) were illuminated by red and green wavelengths respectively and their recorded intensity distributions are shown in Figs. 1(e) and 1(f) respectively. The reconstruction results by cross-correlating 1(e) and 1(f) with 1(c) and 1(d) respectively using a non-linear reconstruction method are shown in Figs. 1(g) and 1(h) respectively [7]. To perform 3D imaging, a synthetic intensity distribution was constructed based on the linearity in intensity of the system by summing the matrices of 1(e) and 1(f) with a relative lateral displacement. The synthetic intensity pattern was reconstructed using the red and green PSFs and the corresponding reconstructed results are shown in Figs. 1(j) and 1(k) respectively. While the proposed method is effective for multidimensional and multispectral imaging with a high light throughput and signal to noise ratio than its' precursors, the cost of the system is significantly higher due to the costs associated with manufacturing QRL using electron beam lithography. A completely low-cost 4D imaging system has been developed by replacing the QRL fabricated by electron beam lithography by a QRL manufactured by grinding refractive lenses using sandpaper with different grit sizes. An image of the top surface of a refractive lens with a focal length of 10 cm with a minimum feature size of 100 μm is shown in Fig. 2(a). The speckle pattern was recorded using a web camera (Quantum QHM495LM) after detaching the lens. The image of the speckle pattern for He-Ne laser (632.8 nm) is shown in Fig. 2(b). The PSF for another plane and green colour was synthesized by the scaling approach discussed in [4,5] as shown in Fig. 2(c). Two synthetic objects "OSA" and "Optica" were used for the demonstration of 4D imaging. The intensity distribution for the object "OSA" for red wavelength and "Optica" for green wavelengths are shown in Fig. 2(d) and 2(e) respectively. The sum of the two intensity distributions is shown in Fig. 2(f). The reconstructed images at the two planes using the two PSFs are shown in Figs. 2(g) and 2(h) respectively.

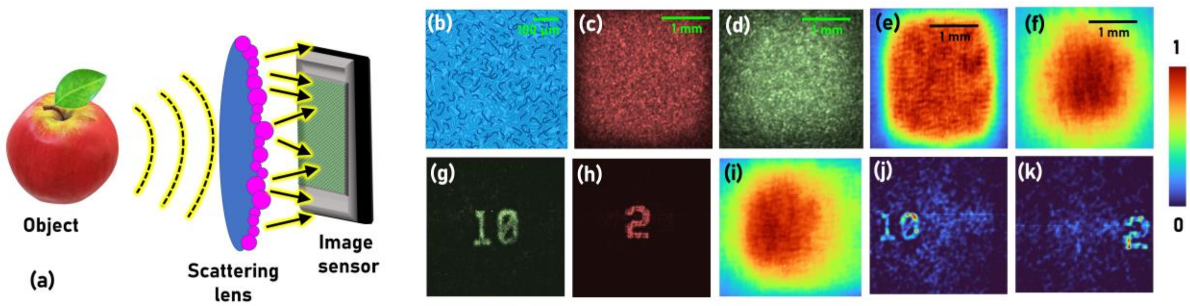

Figure 1. (a) Optical configuration of the imaging system. (b) Optical microscope image of a QRL. Recorded PSFs for (c) red and (d) green wavelengths at 10 cm and 9 cm of object distances respectively. Recorded object intensity distributions for (e) NBS and (f) USAF object. Reconstruction results for (g) NBS and (h) USAF object. (i) Synthetic hologram obtained by summing (e) and (f) with a relative lateral shift. (j) and (k) Reconstruction results of (i) by non-linear reconstruction using (c) and (d) respectively. Colors in (c), (d), (g) and (h) are synthetic.

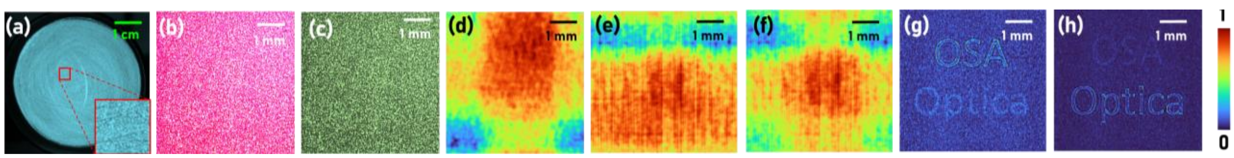

Figure 2. (a) Image of the scattering lens. (b) Recorded PSF for red and (c) synthesized PSF for green wavelength for 10 cm and 9 cm object distances respectively. Synthesized object intensity distributions for (d) 'OSA' object and (e) 'Optica' object for red and green wavelengths respectively. (f) Synthetic hologram obtained by summing (d) and (e) with a lateral shift. (g) and (h) Reconstruction results of (f) by non-linear reconstruction using (b) and (c) respectively.

3. Conclusion

Four-dimensional imaging using QRL has been demonstrated for optical elements fabricated using electron beam lithography and lens grinding. The preliminary results are promising with a high signal to noise ratio and light throughput which may lead to the development of versatile low-cost multispectral and multidimensional imaging systems in the future. With the recent change of focus towards using deterministic optical fields due to the low signal to noise ratio associated with chaotic coded apertures, the current results will support future developments in the area [8].

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